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Editorial Comment

Spectral and Temporal Interrogation of Signal-Averaged Electrocardiograms: The Best Is Yet to Come*

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Improved methods for detecting individual patients at increased risk for sudden cardiac death are essential to reducing mortality from sustained ventricular arrhythmias. Several investigators (1–11) have detected altered time (1–6) or frequency (7–11) components in the terminal QRS complex of signal-averaged electrocardiograms (ECGs) obtained during sinus rhythm from patients and from experimental animals with sustained ventricular tachycardia. The reported incidence rates of these findings have ranged from 60% to 93% depending on the method of signal processing, the definition of abnormal results and the patient groups studied.

Frequency versus time domain analysis. Some investigators (12–17) have attempted to establish the superiority of one approach over the other. The implications of results are unclear because the field continues to evolve rapidly and findings are discordant. Methodologic differences have precluded determination of whether disparate results are due to differences in data processing or conceptual deficiencies with individual approaches.

Fast Fourier transform analysis is a powerful analytic method that decomposes a complex periodic waveform into a sum of harmonically related sinusoids (18). The fundamental frequency is set by the length of the overall sequence. The Fourier transform is unique and no information is lost in transforming a signal from one domain to the other. As long as the sample rate is at least twice the highest frequency in the ECG, the discrete Fourier transform components are samples of a scaled version of the continuous Fourier transform of the original, continuous ECG.

Even though the informational content in time and frequency domain representations of a periodic waveform is equivalent, the extent to which each can depict components of interest depends on the signal being analyzed. Because the Fourier transform is a complete description of the ECG and contains information that may not be seen in the output of a particular fixed band filter, it offers several advantages for the identification and characterization of ECG signals.

In this issue of the Journal, Pierce and coworkers (17) confirm the power of frequency analysis for identifying patients with sustained ventricular tachycardia. Their study also underscores key issues that have fueled debate and it typifies the limitations encountered in published studies comparing time and frequency domain approaches.

ECG lead system. The frequency content of ECG signals is spatially variable and thus lead-dependent (19). Indexes derived from spectra of uncorrected bipolar leads (12–17) may not be comparable with end points and approaches developed with use of Frank (7–11) or other corrected leads. Frank orthogonal leads (20) offer several biophysical advantages over uncorrected bipolar leads, including a more accurate representation of the spatial distribution of the ECG signals of interest because they take torso shape into account. Therefore, Frank leads enable a more accurate estimate of the cardiac source of signals of interest and possibly a more reproducible approach for comparing results among patients.

Time domain analysis has been performed on the terminal 40 ms of an amplified and filtered vector magnitude QRS complex computed from bipolar ECG leads (4). In contrast, most studies (7–11) with frequency analysis have calculated the Fourier transform to estimate scalar lead spectra of the terminal QRS and ST segment of individual X, Y and Z leads with results expressed as an average of the relative contributions of specific frequencies in each lead that constitute these ECG segments. Averaging results of analysis of individual X, Y and Z spectra, which is a linear operation, cannot in general be compared with measures derived by combining leads in a nonlinear operation such as the vector magnitude (11). Furthermore, some commercial systems employ notch filters known to distort phase and magnitude (13).

Therefore, ECG waveforms analyzed with current time and frequency domain procedures differ markedly. The fixed band pass filters that enable visual detection of late poten-

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tials in a vector magnitude or individual leads may differ from the range of frequencies identified with use of Fourier analysis of individual X, Y and Z ECG signals that distinguish patients with from those without ventricular tachycardia.

Direct current components. Procedures to eliminate spectral distortion due to direct current components remain controversial. In the absence of a window function, the mean value of the signal transformed does not affect the spectrum except at 0 Hz because the Fourier transform of the mean value of the ECG segment is an impulse at 0 Hz. In contrast, the mean value of the segment does alter the spectrum when multiplied by a window function. Multiplication of a signal by a window function is mathematically equivalent to convolution of the Fourier transform of the signal and the window function. The convolution of any function with an impulse yields a replica of that function. Thus, the direct current term in the ECG segment adds a scaled version of the window spectrum to the spectrum of the windowed segment. Accordingly, subtracting the direct current component after windowing (15,17) does not eliminate spectral distortion due to direct current components.

The spectrum of a window is dependent on its length. In previous studies (10,11), the data interval (terminal 40 ms of the QRS complex plus ST segment) averaged 150 ms (10,11). The main lobe of the spectrum of a 150 ms, four-term Blackman-Harris window is down 7 dB at 10 Hz, down 33 dB at 20 Hz and by 27 Hz the main lobe has reached the 92 dB floor. Accordingly, the effects of the mean value of the ECG data interval are minimal at frequencies above 10 Hz. Consequently, we have excluded frequencies below 10 Hz from analysis.

A more fundamental issue is identification of the appropriate electrical reference for measuring direct current components during the terminal QRS and ST segment. The direct current component measured during the PR interval may differ markedly from that measured during the TP or ST segment. Moreover, subtracting the mean value of the terminal QRS/ST segment data interval changes the biologic signal because inherent ST segment elevation or depression is lost.

Our approach to short segment analysis has been not to subtract the direct current term before windowing because it is not yet clear what electrical reference in the terminal QRS and ST segment is biologically meaningful (7–11).

ECG interval analyzed. Controversy over the optimal ECG interval for interrogation stems in part from the methodologic differences already discussed. In addition, the cardiac source of altered frequency components in ECG signals detectable by Fourier analysis has not yet been characterized definitively. In the present study, Pierce and coworkers (17) estimate the spectra of late potentials detectable with time domain techniques. Their approach analyzes a fixed data interval containing the late potential. Results demonstrate that spectral features of late potentials enable better separation of patient groups than that achievable with traditional time domain measures. One advantage of this approach is that the data interval is defined automatically. On the other hand, such rigidity assumes that this 120 ms interval within the cardiac cycle is optimal for identifying patients prone to ventricular tachycardia and it assumes that altered time and frequency components detectable in ECG signals are a measure of the same pathophysiologic process.

Our approach has been to interrogate biologic intervals rather than to impose a predetermined, fixed data interval (7–11). We have analyzed the terminal 40 ms of the QRS complex and the natural ST segment of scalar ECGs recorded at a gain of 1,000 regardless of the presence or absence of late potentials. In our laboratory, all records are sampled at 1 KHz and the interval transformed always contains 512 samples. Thus, the fundamental and therefore the frequency separation between lines in all cases is fixed at 1.953 Hz. As long as the signal, regardless of length, is within the 512 samples transformed, that signal's continuous Fourier transform will be consistently sampled and will enable comparisons among patients.

Delineation of the pathophysiologic determinants of the altered frequency components in ECG signals from patients with ventricular tachycardia is paramount for determining the optimal ECG interval for analysis. Studies (1,2,21) have demonstrated a correlation between late potentials detected in the time domain and delayed ventricular activation detected in the course of cardiac mapping. Although delayed ventricular activation is likely to be responsible in part for the altered frequency content of ECG signals from patients with sustained ventricular tachycardia, the observation (10,15–17) that results are independent of QRS width (including bundle branch block) suggests that derangements in ventricular conduction in addition to the total duration of ventricular activation contribute to the generation of abnormal frequency components. Concomitant excitation of normal myocardium and myocardium that has undergone infarction will generate QRS complexes that reflect heterogeneities in the pattern and phase of activation even though the total duration of ventricular activation may be comparable with that from patients without ventricular tachycardia. Thus, late potentials may be only one hallmark of an anatomic/electrophysiologic substrate conducive to the development of sustained ventricular arrhythmias but should not be viewed as the sole generator of the altered frequency components detectable in ECG signals from patients with ventricular tachycardia.

Objectives of future research. The impact of time and frequency analysis of ECG signals on patient care will depend on the extent to which results prospectively contribute to clinical decision making. Some prospective studies with time domain approaches have demonstrated that, among patients convalescing from myocardial infarction, the

likelihood of spontaneous ventricular tachycardia is greater in those who have an abnormal than in those who have a normal signal-averaged ECG (22–24). However, the low positive predictive accuracy underscores the need for continued refinements in methods of data analysis. Additional studies that rely on commercial systems to detect altered time and frequency components in the terminal QRS/ST segment are unlikely to provide new insights into the critical issues that must be resolved. The next important issue is not whose index best distinguishes patients with known ventricular tachycardia from those without, but what refinements are required to extract information from ECG signals that best reflects the electrophysiologic/anatomic derangements unique to patients prone to life-threatening ventricular arrhythmias. Real advances will evolve from studies that elucidate the electrophysiologic determinants of altered time and frequency components, the specific range of frequencies generated by these electrophysiologic derangements, their temporal distribution during the cardiac cycle and their spatial distribution on the body surface.

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